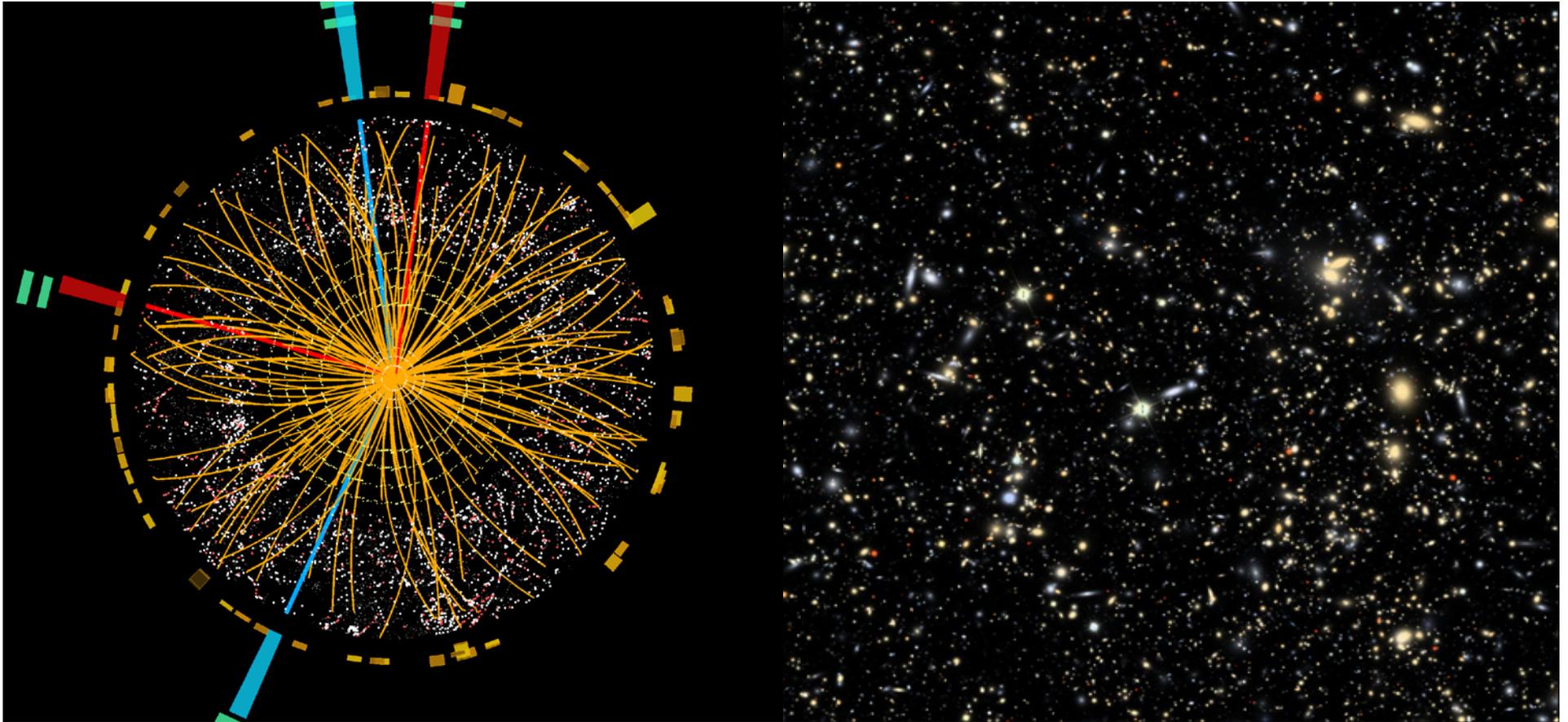


Particle Physics from Cosmic Surveys: Overview of Opportunities

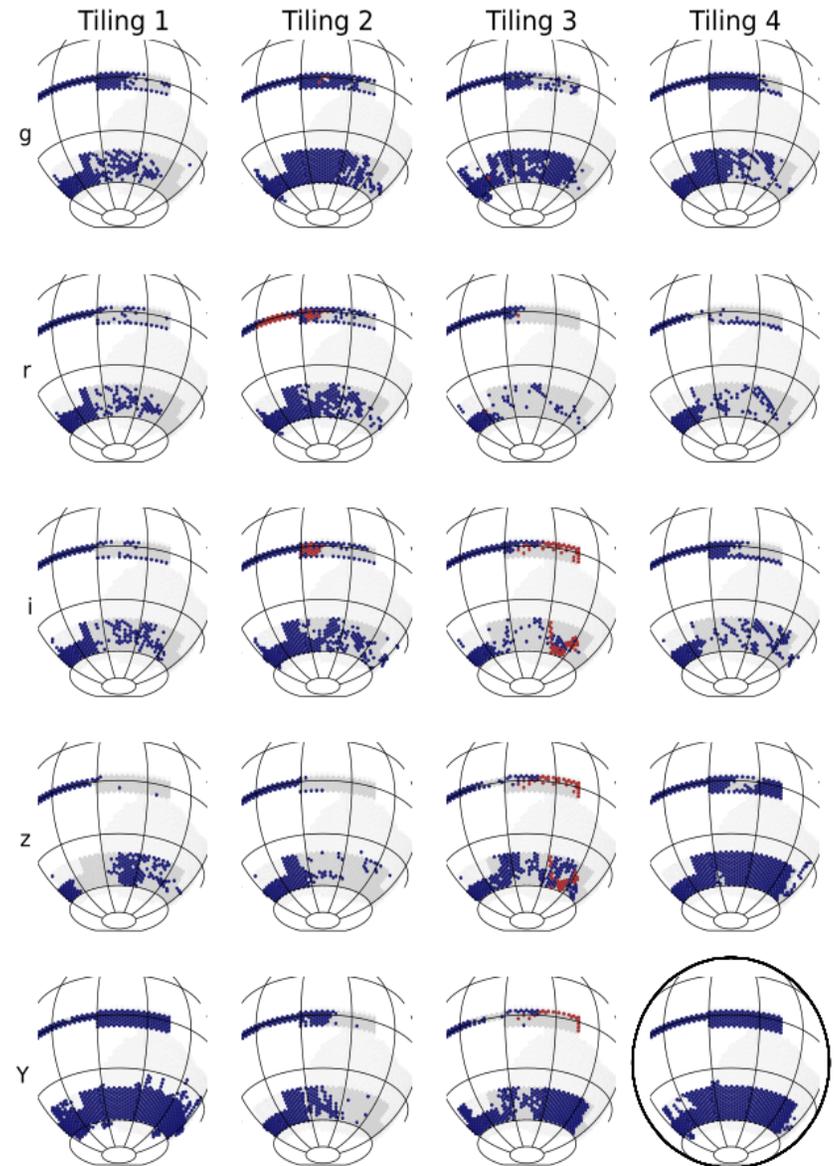


Klaus Honscheid
Ohio State University
P5 Meeting @ SLAC

A New Era of Precision Cosmology

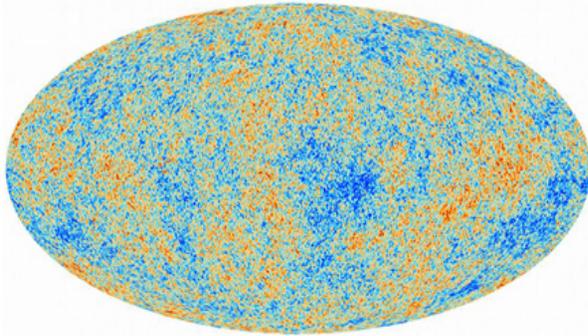
Dark Energy Survey began on Aug 31, 2013. It runs until 2018.

First Stage III Imaging Project with an instrument optimized for Dark Energy

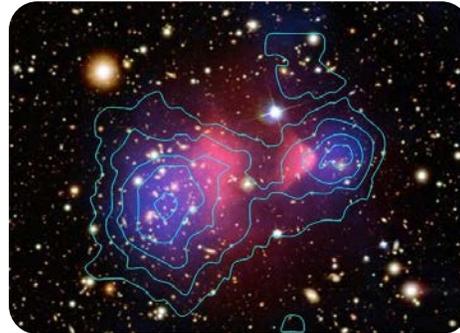


Mapping the Universe

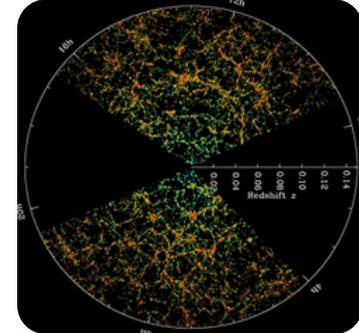
CMB (Planck)



Bullet Cluster (X-Rays, Weak Lensing)



SDSS-III Galaxies



With these maps Cosmic Surveys address some of the most fundamental questions in Physics:

- The Nature of Accelerating Expansion of the Universe
- Dark Energy or Modified Gravity
- Neutrino Properties
- Dark Matter
- Physics at the Inflation Scale

Typical Scales

$$m_{\text{DE}} \sim 10^{-33} \text{ eV}$$

$$m_{\text{DM}} \sim 100 \text{ GeV}$$

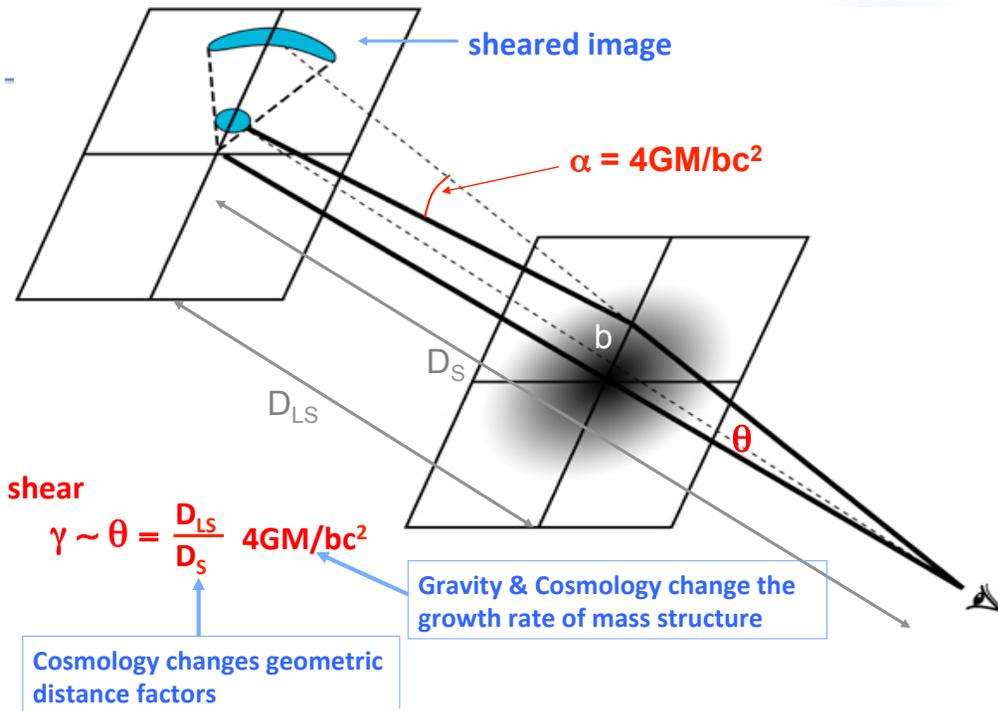
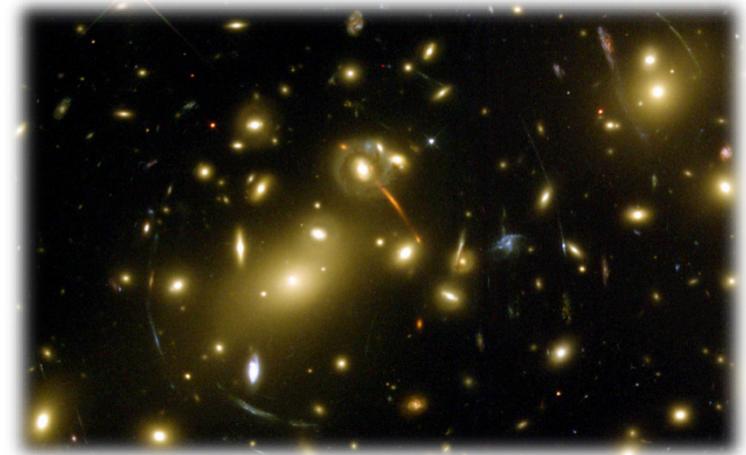
$$\text{Inflation} \sim 10^{16} \text{ GeV}$$

Imaging Surveys

- Galaxies – Position, Magnitude, Shapes

- Weak Lensing

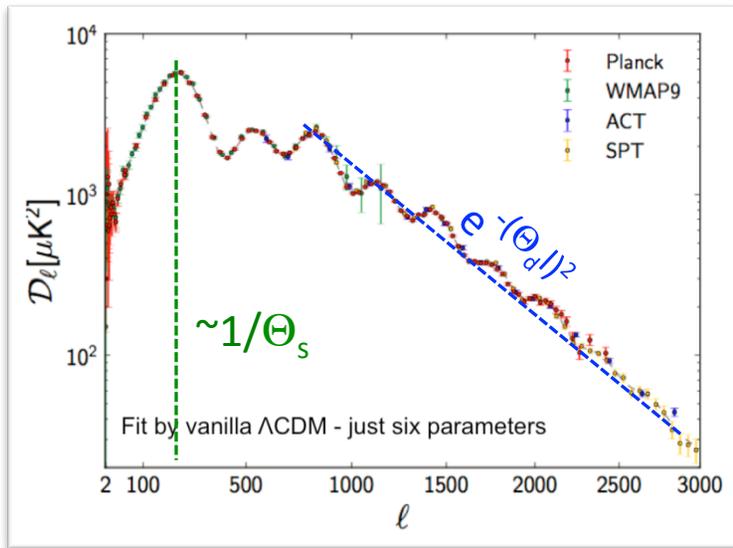
- Shear
- Magnification



- Galaxy Clusters
- Photometric redshifts
- Supernovae
- Strong Lenses (Time Delay)

[T. Tyson]

Cosmic Microwave Background

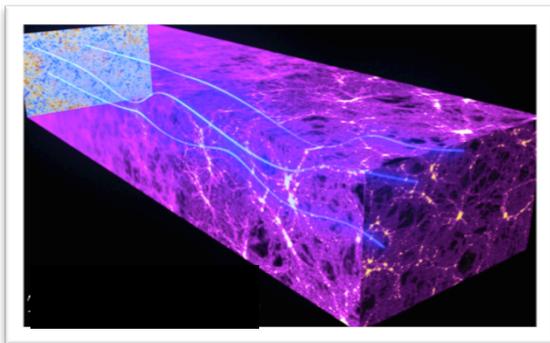
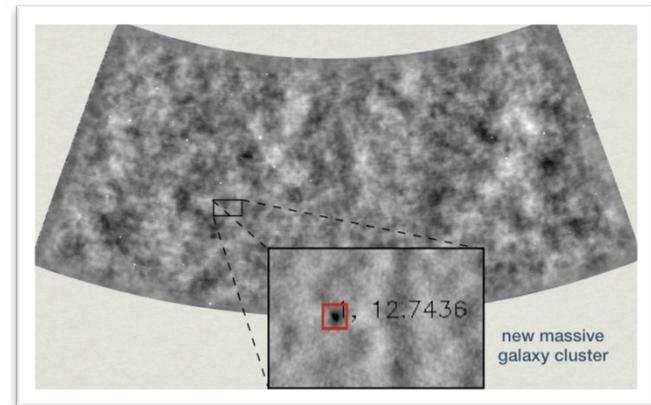


Temperature Anisotropy

- Inflation Checks
- Θ_s is the sound horizon (BAO)
- Θ_d is the damping scale (N_{eff})

Sunyaev–Zel'dovich effect

Detect perturbations (== clusters) using inverse Compton scattering on hot gas (electrons)



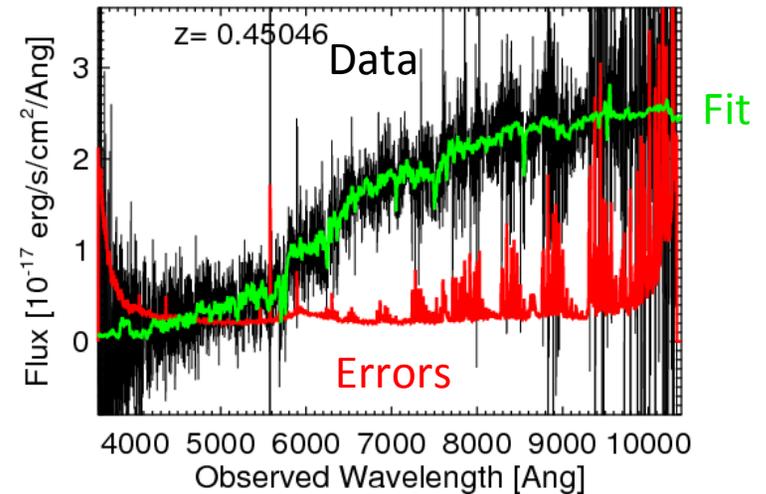
CMB Lensing

$$\tau(\hat{n}) \rightarrow \tau(\hat{n} + \nabla\phi(\hat{n}))$$

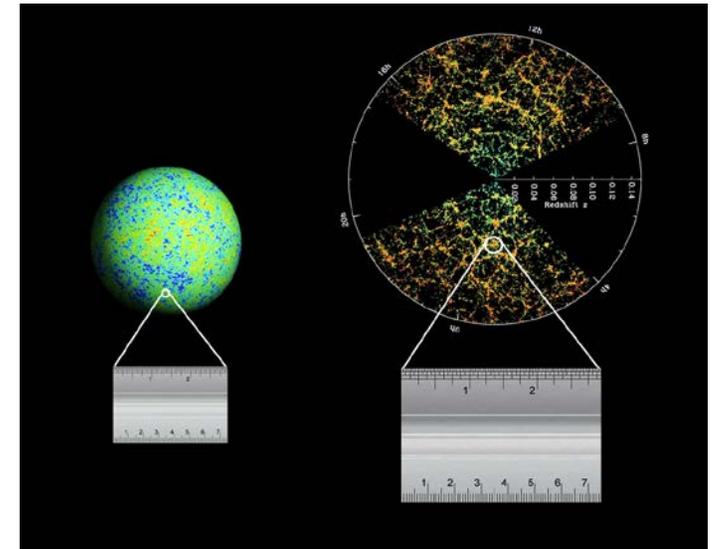
(B-mode) Polarization

Spectroscopic Surveys

- Map the 3D distribution of galaxies
 - Angular position from imaging
 - Radial position from redshifts
- Two probes
 - **Redshift Space Distortions**
Peculiar velocities of galaxies to measure growth of structure
 - **Baryon Acoustic Oscillations**
A standard ruler to measure expansion

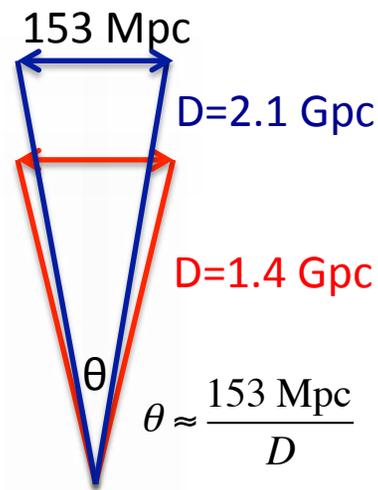


BOSS

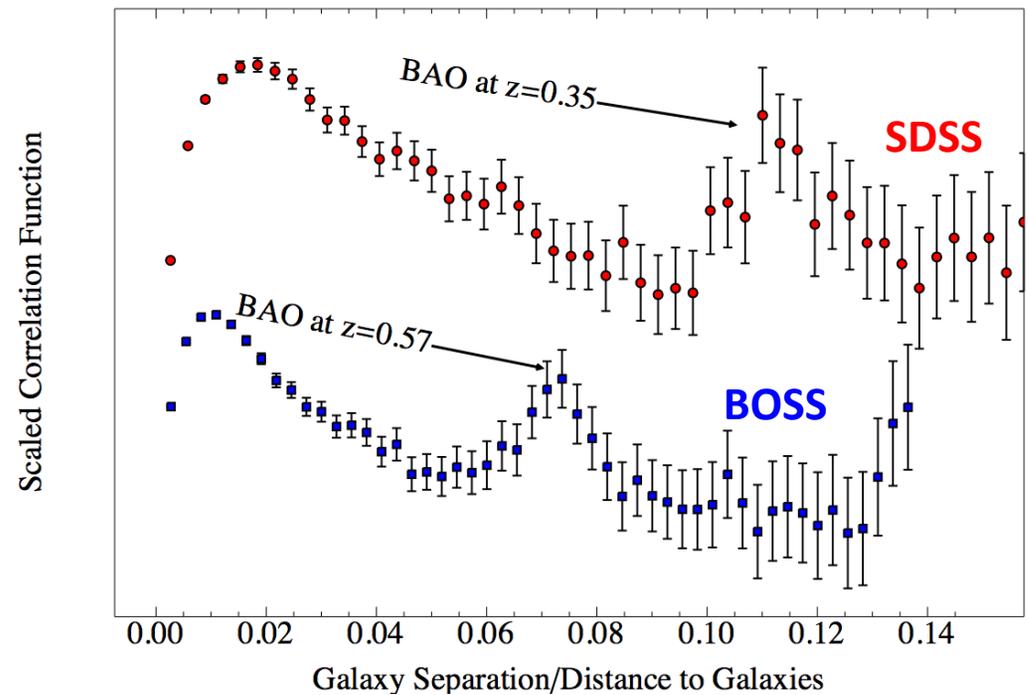


Dark Energy: Distances

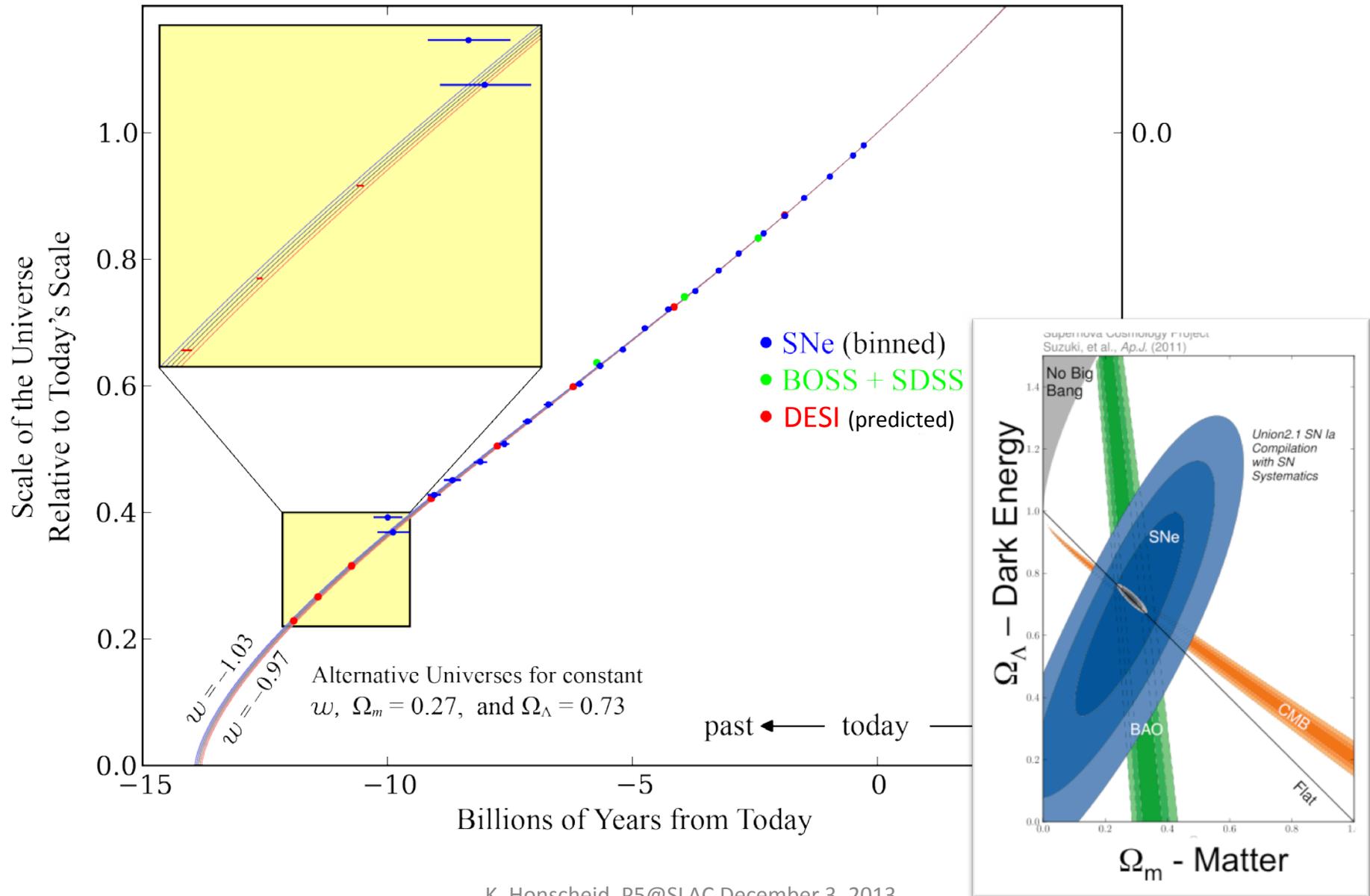
Measure the length of the Standard Ruler at different red shifts to map out the expansion history of the Universe



[M. Levi]

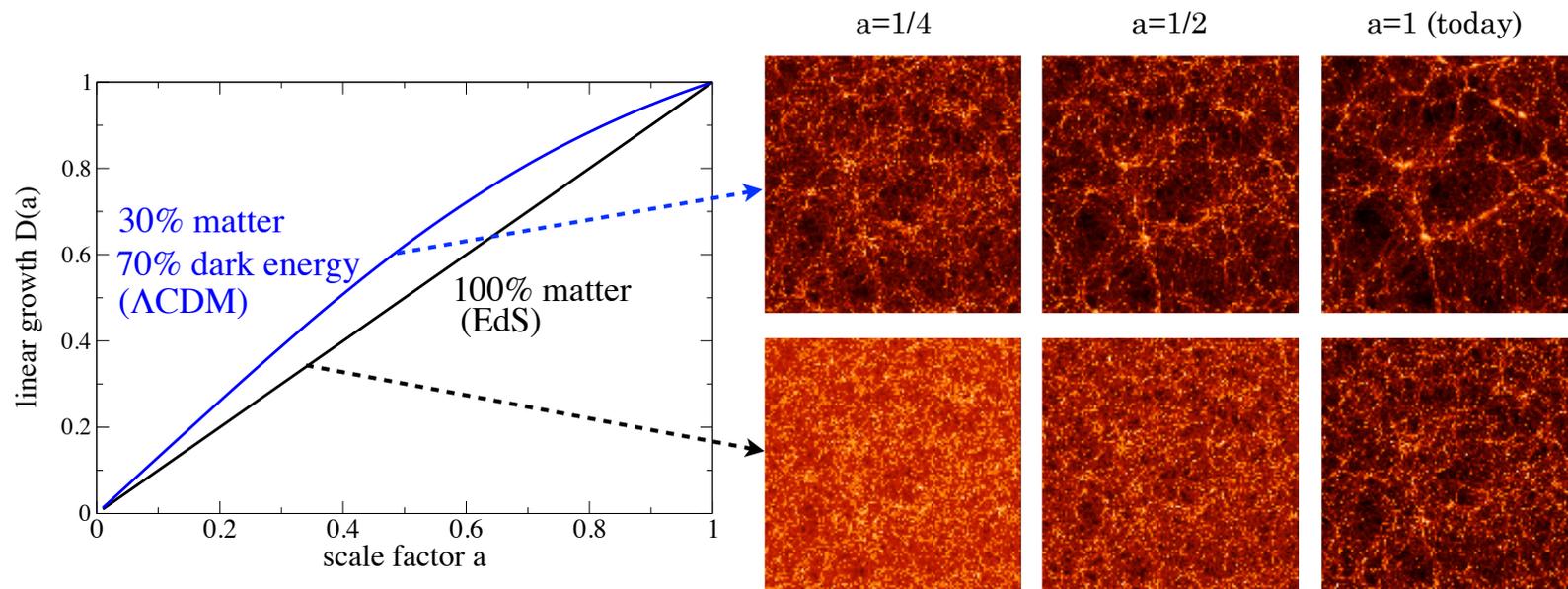


Dark Energy: Distances



Dark Energy: Growth of Structure

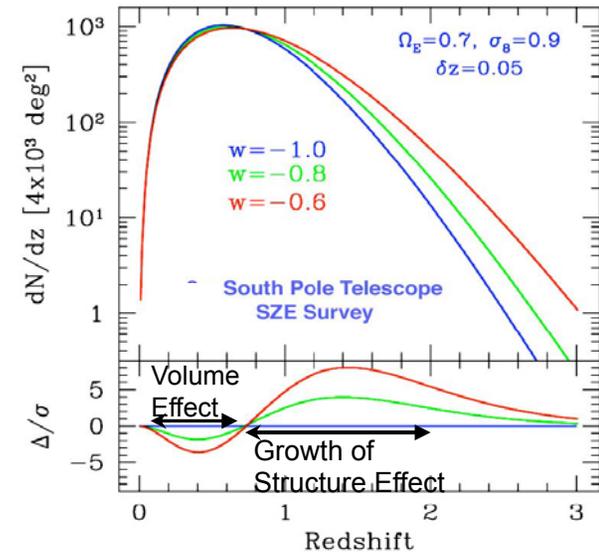
Measure growth of perturbations $\delta(a) = D(a)\delta(a=1)$ with $\delta = \delta\rho / \rho$
DE suppresses growth of density fluctuations



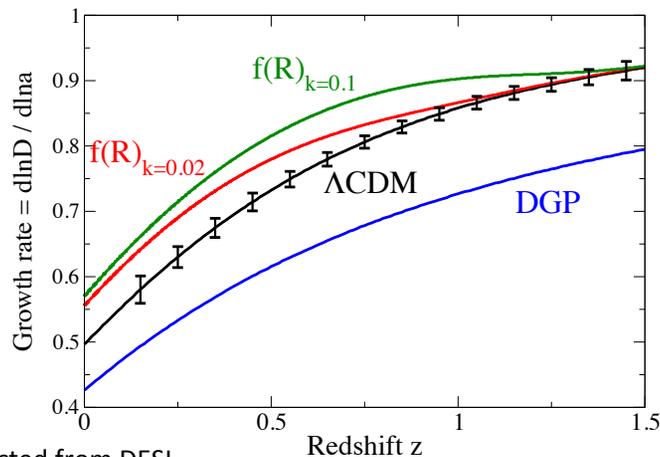
Dark Energy or Modified Gravity

Principle Probes to measure Growth

- Redshift-Space Distortions
- Galaxy Cluster Counts
- Weak Gravitational Lensing



Modified Gravity changes (GR) relation between Growth + Expansion



Errors projected from DESI

- Λ CDM Cosmology
- Different Modified Gravity models
- (all with the same expansion $H(z)$)

Neutrinos

Neutrino number density

$$n_\nu = N_\nu \times \left(\frac{3}{11}\right) n_\gamma \approx 340 \text{ cm}^{-3}$$

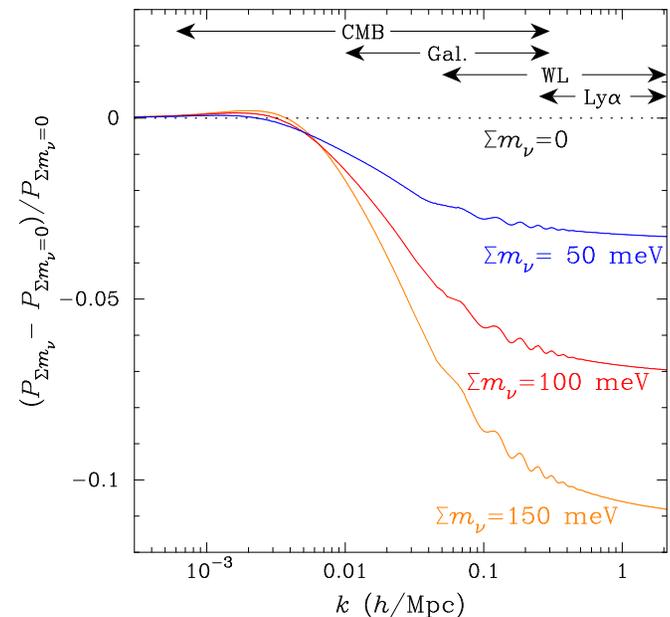
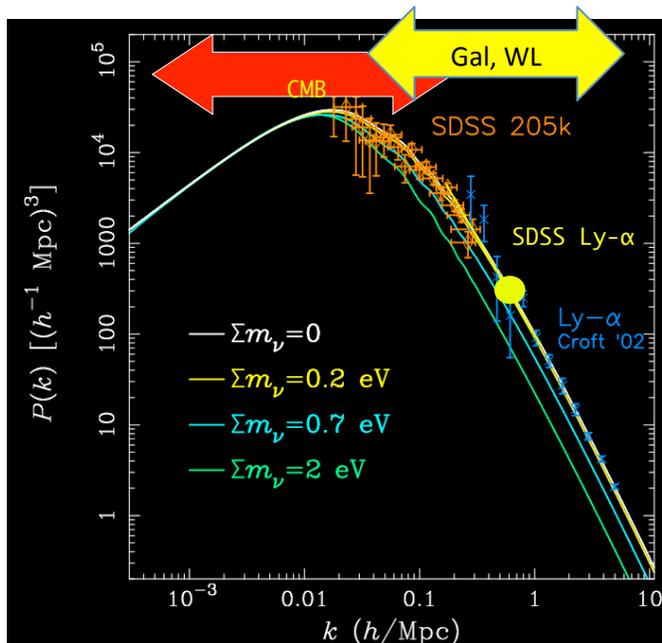
N_{eff} from CMB Damping and phasing of acoustic peaks

(for standard 3 ν 's $N_{\text{eff}} = 3.046$)

$$N_{\text{eff}} = 3.30 \pm 0.27 \quad [\text{Planck}]$$

$$N_{\text{eff}} = 0 \text{ excluded at } > 10 \sigma$$

Sum of the neutrino masses affects the Power Spectrum



Neutrinos

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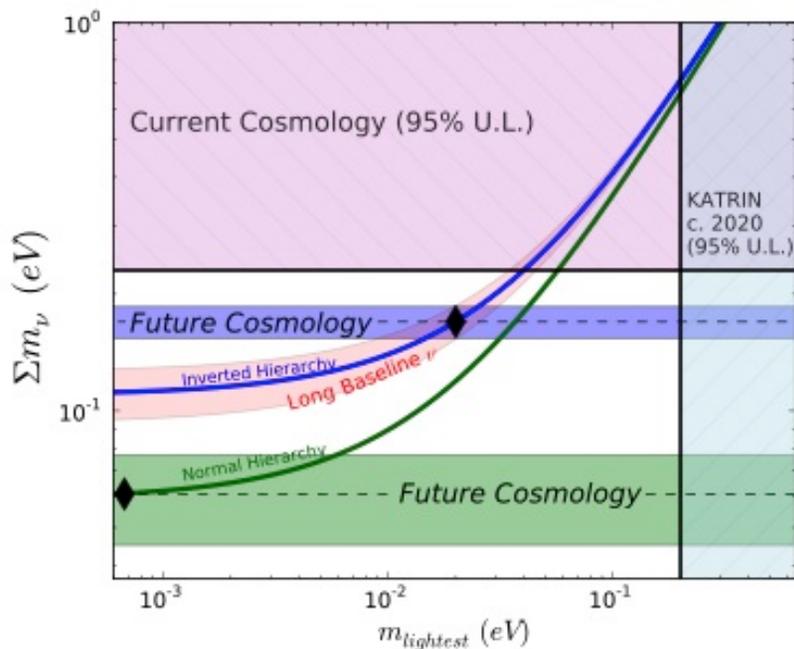
N_{eff} from CMB Damping and phasing of acoustic peaks

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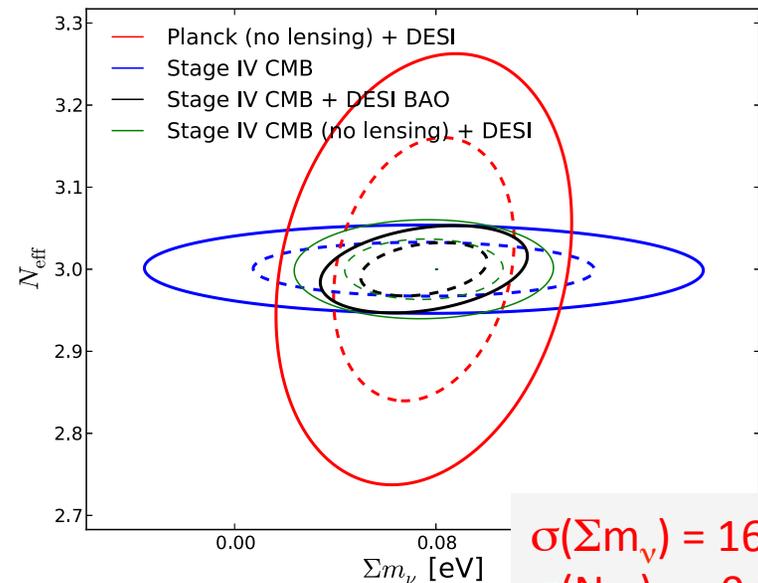
$$N_{\text{eff}} = 3.30 \pm 0.27 \quad [\text{Planck} + \text{BAO}]$$

$$N_{\text{eff}} = 0 \text{ excluded at } > 10 \sigma$$

Sum of the neutrino masses affects the Power Spectrum



Stage IV Projections $N_{\text{eff}} - \Sigma m_\nu$



$$\sigma(\Sigma m_\nu) = 16 \text{ meV}$$

$$\sigma(N_{\text{eff}}) = 0.020$$

Inflation

(Single field) Inflation Predicts

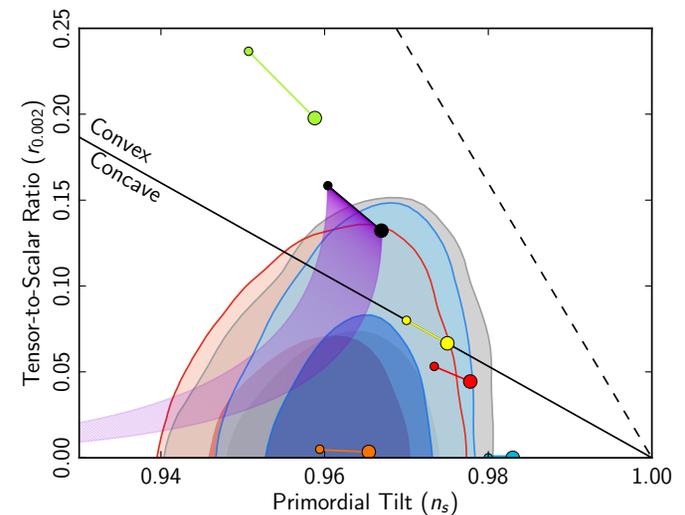
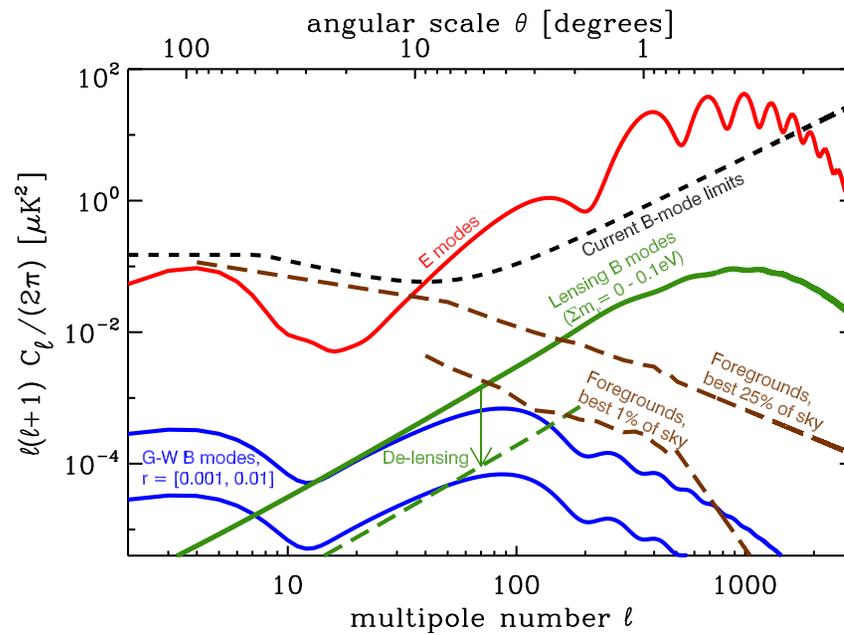
- Flat universe with nearly scale invariant fluctuation spectrum
- Gravity waves
- Nearly Gaussian density fluctuations
- Homogeneous and isotropic universe

$$n_s = 0.960 \pm 0.0073 \text{ [Planck]}$$

Tensor/Scalar ratio r

$$f_{\text{NL}}(\text{local}) = 2.7 \pm 5.8 \text{ [Planck]}$$

LSST



Need B mode polarization to improve r

Support from High Energy Theorists

Snowmass CF-5 Inflation Science Letter of Support

September 3, 2013

Jonathan Bagger, Tom Banks, Savas Dimopoulos, Scott Dodelson, Jonathan Feng, Steve Giddings, Sheldon Glashow, Daniel Green, Sean Hartnoll, JoAnne Hewett, Shamit Kachru, Renata Kallosh, Nemanja Kaloper, Jared Kaplan, Marc Kamionkowski, Matthew Kleban, Igor Klebanov, Lloyd Knox, Albion Lawrence, Andrei Linde, Juan Maldacena, Emil Martinec, Ann Nelson, Maxim Perelstein, Michael Peskin, Joseph Polchinski, John Schwarz, Nathan Seiberg, Leonardo Senatore, Stephen Shenker, Eva Silverstein, Mark Srednicki, Andy Strominger, Edward Witten, Matias Zaldarriaga

September 3, 2013

Cosmic inflation is the leading theory for the origin of structure in the universe. Proposed in the early 1980s to explain the apparent smoothness and flatness of the universe, it was soon realized that quantum fluctuations generated during inflation would eventually evolve into the distributions of dark matter and galaxies we observe today. Inflation drives the spatial curvature to nearly zero, and introduces density perturbations that are adiabatic with a nearly scale in-

http://www.snowmass2013.org/tiki-download_file.php?fileId=321

Cosmic Surveys and Dark Matter

To date **only** evidence for Dark Matter comes from **cosmic surveys**.

Only gravitational effects have been observed

Cold, collisionless DM (CDM) **agrees well** with cosmological data.

Might **breakdown** at galactic or smaller scales

- Number of Dark Matter Halos
- Dark Matter Profiles (Cored Profiles)



Dwarf Galaxies: Great DM Laboratory

$$M^* \sim 10^6 M_{\text{Sun}}$$

$$M_{\text{DM}}/M^* \sim 50$$

DM dominated

Easy(ier) to interpret

Very few stars

Less baryonic, SN influence

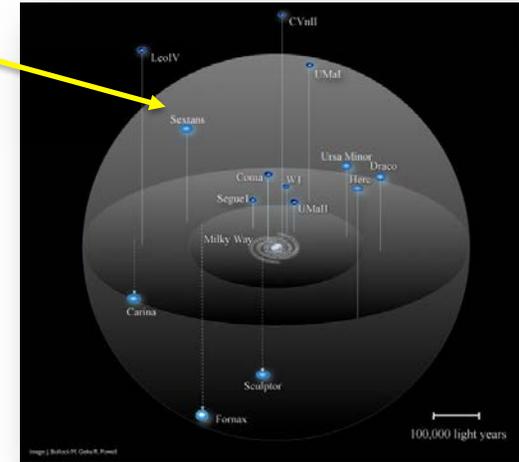
[Targets for Fermi and Gamma Ray Telescopes]

WDM and SiDM

Many DM Halos in DM Simulations
Few (~20) Milky Way Satellites

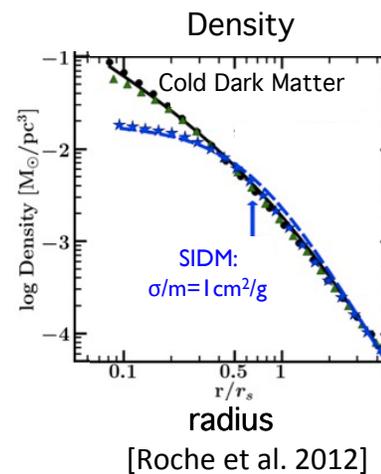
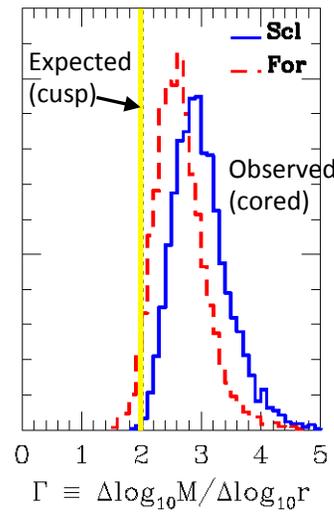


Possible explanations include:
Tidal forces, Baryonic effects,
Warm Dark Matter ($m_{DE} \sim 1 \text{ keV}$)
Ultra-faint dwarf galaxies
DES (LSST) could find > 30 (150)
[Tollerud et al. APJ 688, 2008,
Bullock, Garrison-Kimmel, Boylan-Kolchin, Peter]



Mass Profiles in MW dSph Satellites

[Walker, Penarrubia APJ 742 2011]



Self-Interacting DM

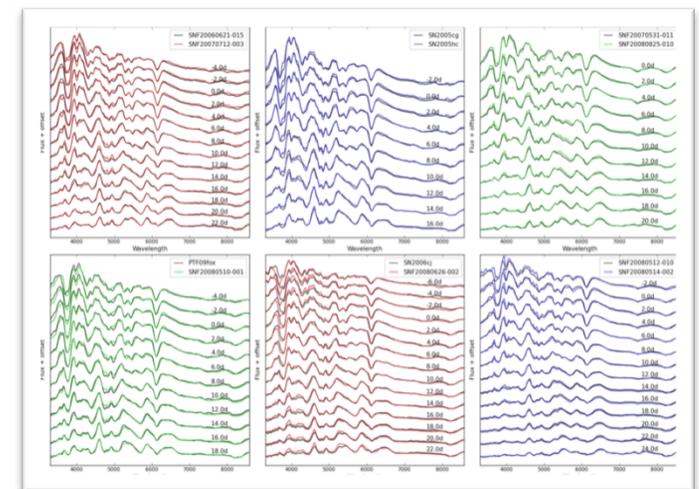
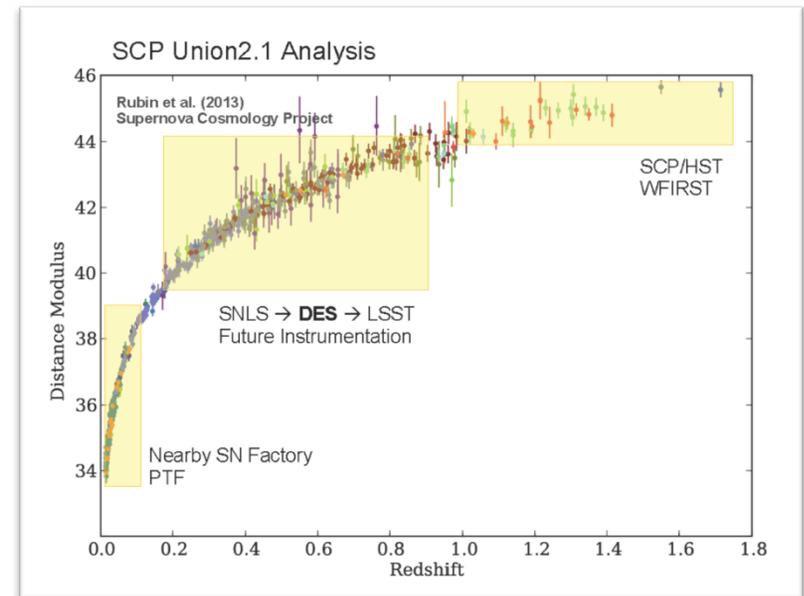
e.g. Hidden Sector Models with a heavy photon mediator and $\sigma/m_{DM} \sim 2 \text{ barns/GeV}$

Simulations give same large scale structure but differences at small scales

See Snowmass Dark Matter Complementarity Report for details

Synoptic Surveys

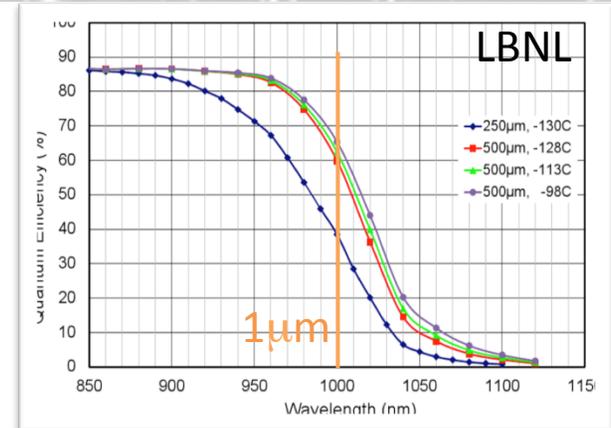
- LSST will detect $\sim 100,000$ SNe 1a
- 100-fold increase over current samples
- Opportunities at low redshift
 - Identify key SN 1a and host features
 - Systematic control of SN 1a evolution
 - Example: SN Twins allows control of evolutionary drift (SN, dust)
 - Follow-up campaign for $\sim 50\%$ of low redshift LSST SNe ($0.03 < z < 0.08$) to anchor Hubble diagram
- Opportunities at high redshift
 - Space mission + IFU spectrograph
 - Explore ground based alternatives



Instrumentation R&D

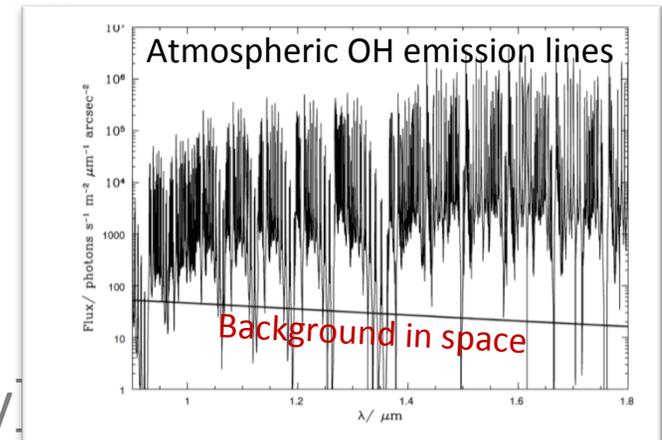
Extend CCD Quantum Efficiency (LBNL)

- NIR requires thicker devices
extends SNe, BAO reach
- Blue end requires thinner window
extends BAO Ly- α range



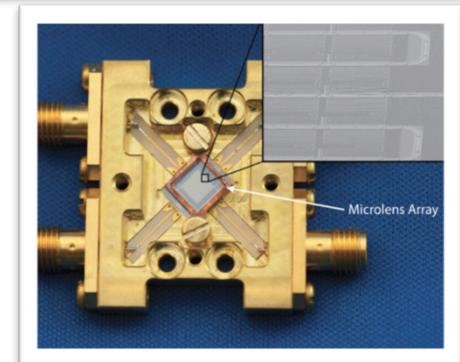
OH Skyline Suppression (Princeton, LBNL...)

- There is space between narrow lines
- Fiber Bragg gratings, Quasi-crystals, Guided Mode Resonance...
- When coupled with adaptive optics could enable NIR spectroscopy without a space mission

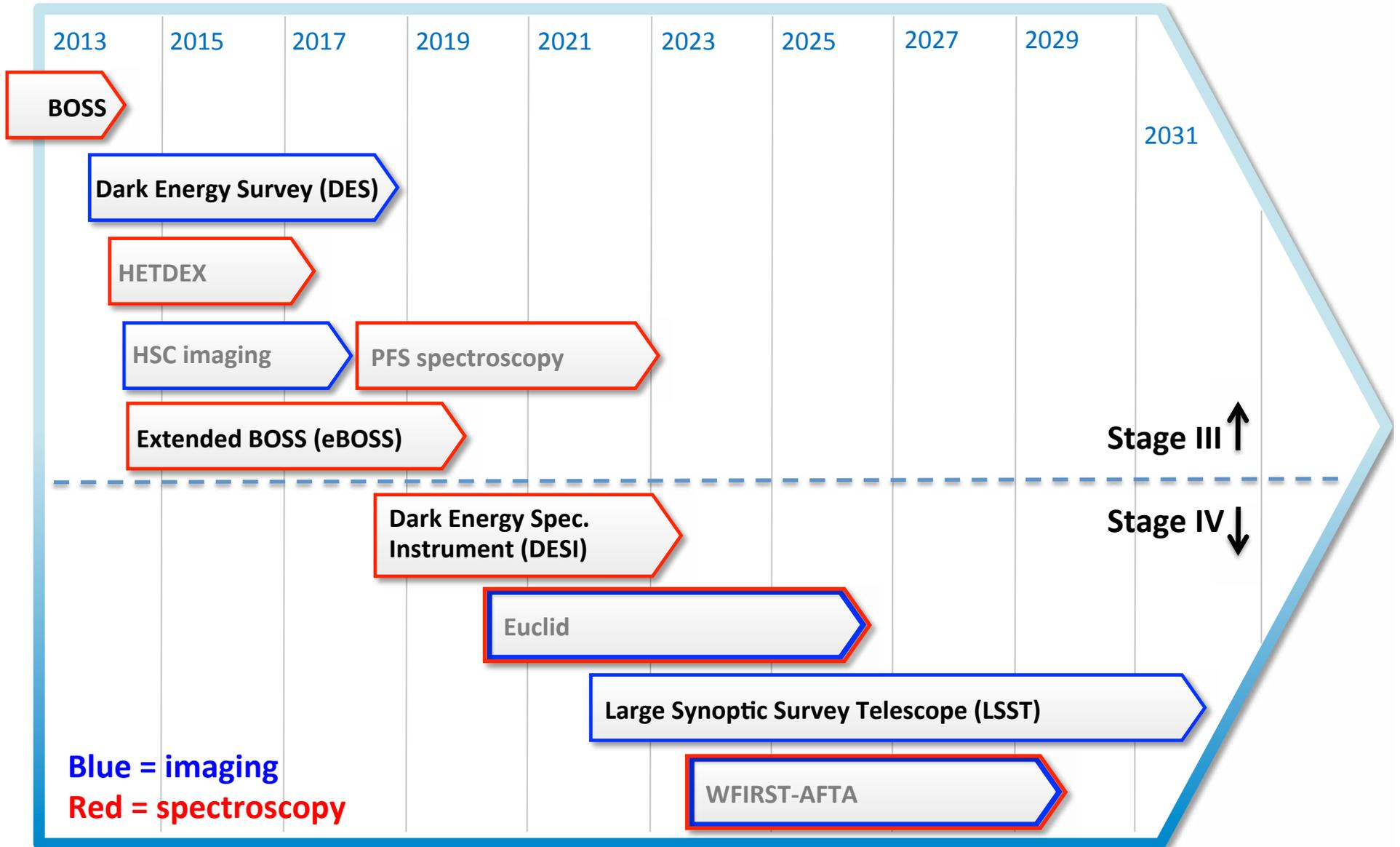


Multi-chroic CMB Detectors [ANL, Berkeley] Spectral Pixels – MKIDS (UCSB, FNAL)

- Large array of superconducting detector elements with energy measurement for individual photons
- Improve $R = \lambda / \Delta\lambda \sim 10$ to $R \sim 100$, Readout, Packaging



Dark Energy Experiments: 2013 - 2031



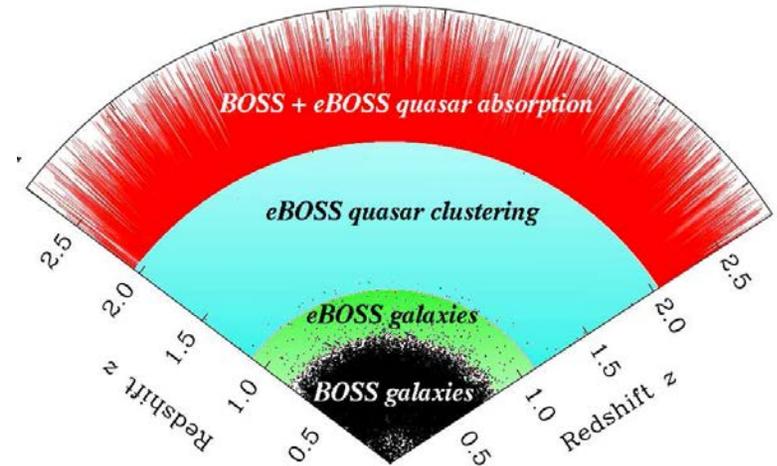
Stage III: eBOSS, SuMIRe

Extension of **BOSS** program

- First BAO measurement in $1 < z < 2$
- Predicted $\Sigma m_\nu < 0.104$ eV
- 7500 deg²; some overlap with DES

Leverage existing facility

- Only operations support requested from DOE



SuMIRe: 1500 deg² imaging and spectroscopic survey on Subaru 8.2m

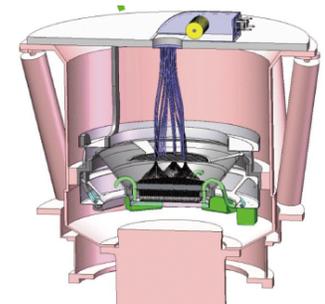


Hyper SuprimeCam

- 1.5 deg imager
- Wide (1500 deg²)
- Deep (26 mag)
- Start in 2014

PrimeFocusSpectrograph

- 2400 fibers
- 380-1300 nm
- Resolution 2000-5000
- Partially funded
- 2018...



Euclid and WFIRST/AFTA

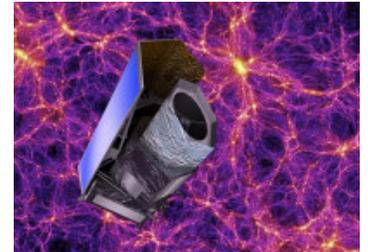
- Space:** + Stable point spread function, NIR, no atmosphere
- Survey area and time, Costs, Complexity

Euclid:

- **Approved** European dark energy satellite mission (2020)
- 15,000 deg² WL survey, single filter, $N_{\text{eff}} \sim 30-40$
- 15,000 deg² BAO survey, $R \sim 250$, 50 million redshifts
- 40 deg² deep survey
- 6.25 year mission at the Earth-Sun L2 point

WFirst/AFTA:

- **Top ranked** space mission in 2010 Decadal Survey
- NASA led project using existing 2.4 m telescope
- 2,000 deg² imaging and spectroscopic survey
- Narrow but deep, $N_{\text{eff}} \sim 70$
- IFU spectrometer for SN program (6 months)
- Possible launch 2023-2024



1.2 m mirror
580 Mpixels
0.4 deg² FOV
0.1"/pixel
36 4kx4k CCDs, 16 H2RG



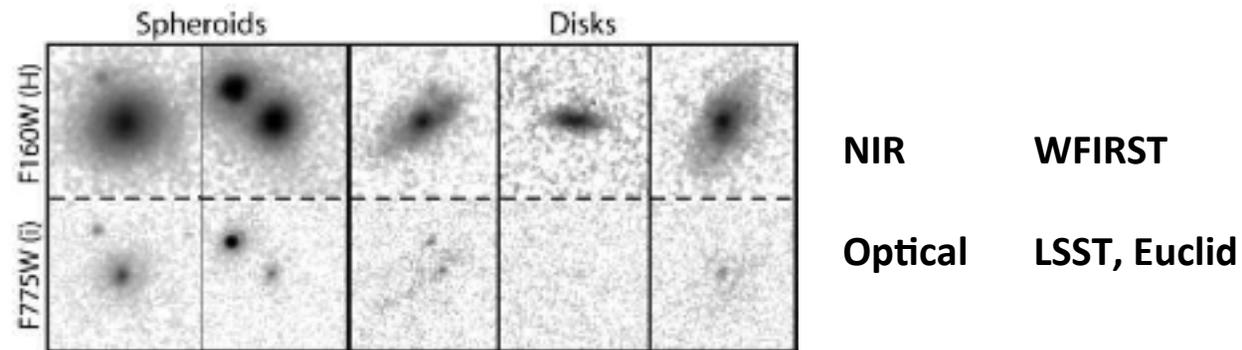
2.4 m mirror
288 Mpixels
0.3 deg² FOV
0.11"/pixel
24 H4RG detectors

Space-Ground Complementarity

Comparable BAO and neutrino precision for DESI and Euclid

Weak lensing from WFIRST/AFTA, Euclid and LSST complementary

- Weak lensing shapes from different wavelengths



- Improved photo-z's from combined filter bands
- Very different systematics, e.g. # of images of a galaxy

	LSST	Euclid	WFIRST
#of exposures	~700 x 15s (r+i)	3 x 600s	16 x 184 s (J, H, F)

Conclusion

Fundamental Physics

Cosmic Surveys address fundamental questions with direct impact on particle physics: Dark Energy, Dark Matter, Inflation, Neutrinos

Leadership

The Cosmic Microwave Background and the Accelerating Expansion of the Universe were discovered by US scientists

World Leadership – a Gem in the US HEP program

Roadmap

Coherent program with complementary experiments.

Reviewed and prioritized by a HEPAP sub-panel just a year ago

Strong endorsement from the CMB + DE community during Snowmass

Support for the Cosmic Frontier



Snowmass Recommendations

During the Snowmass Summer Study the community rallied behind previous reports (DETF, Rocky-III) with the consensus to support these key steps:

Remain a Leader in Dark Energy

- A combination of imaging and spectroscopic surveys is needed to pinpoint the new physics driving the acceleration, the validity of GR, properties of neutrinos, and the physics of inflation.
- The community strongly supports the program of Stage III and Stage IV dark energy experiments and moving forward as quickly as possible with the construction of LSST and DESI.

Build a next generation CMB Polarization Experiment

- A next generation experiment to pin down large field inflationary models, neutrino masses, and N_{eff} .
- The community understands that next generation experiment will require a nationwide coherent effort involving the national labs.

Extend the Reach

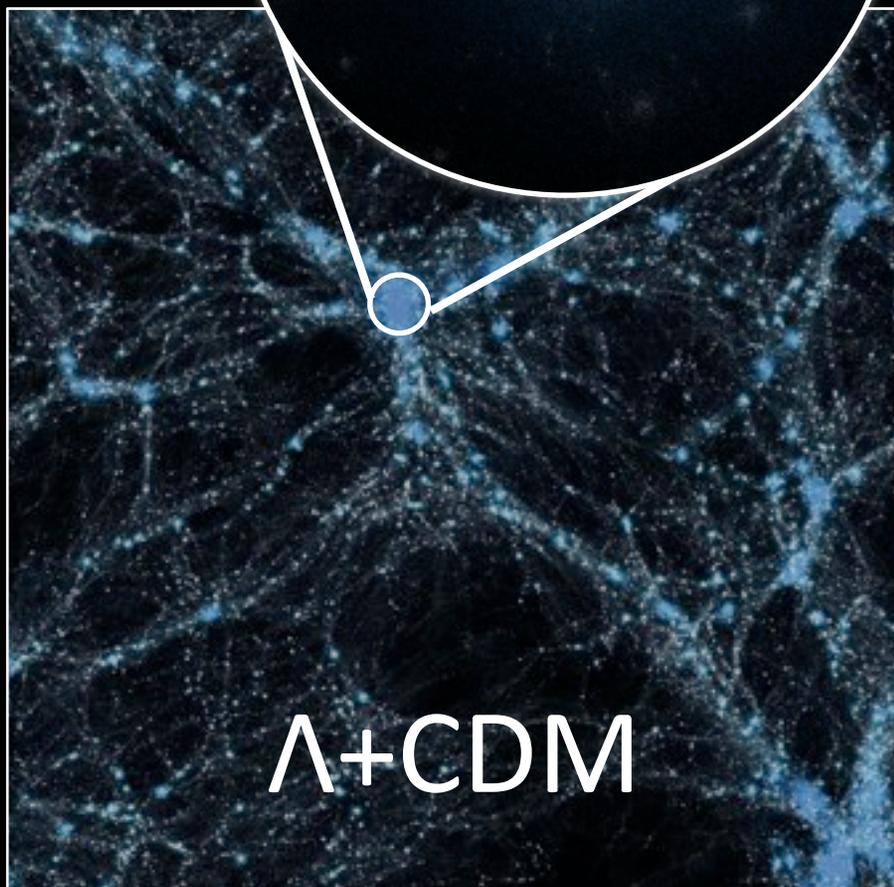
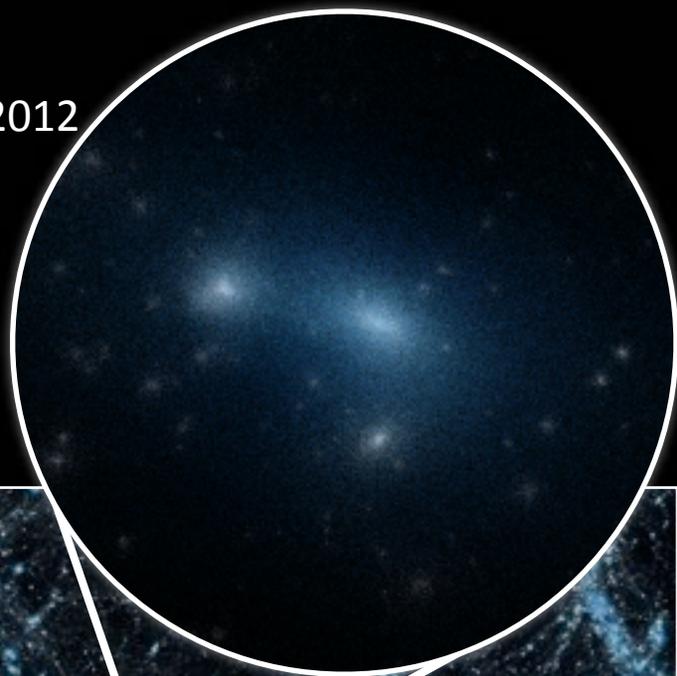
- Targeted spectroscopic campaigns to augment the SN program and to calibrate methods of red shift estimation.
- Continued investment in instrumentation R&D
- Support for theoretical work and small enhancements to the survey program to investigate novel probes of gravity



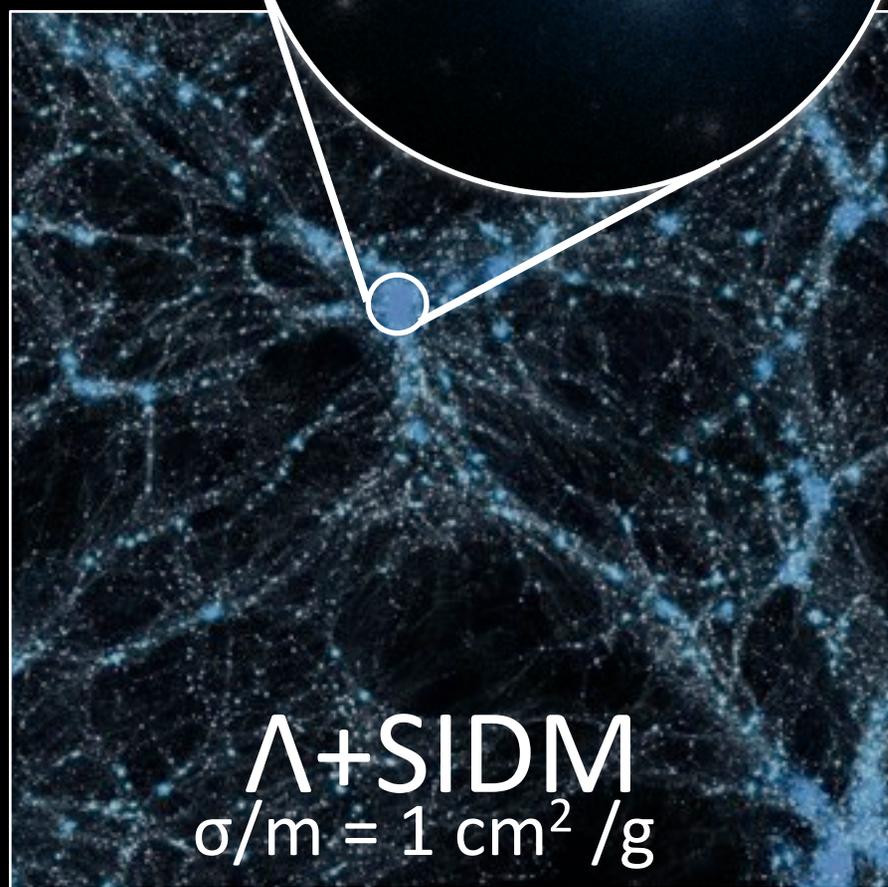
Additional Slides From Other Presentations

Rocha et al. 2012

J. Bullock



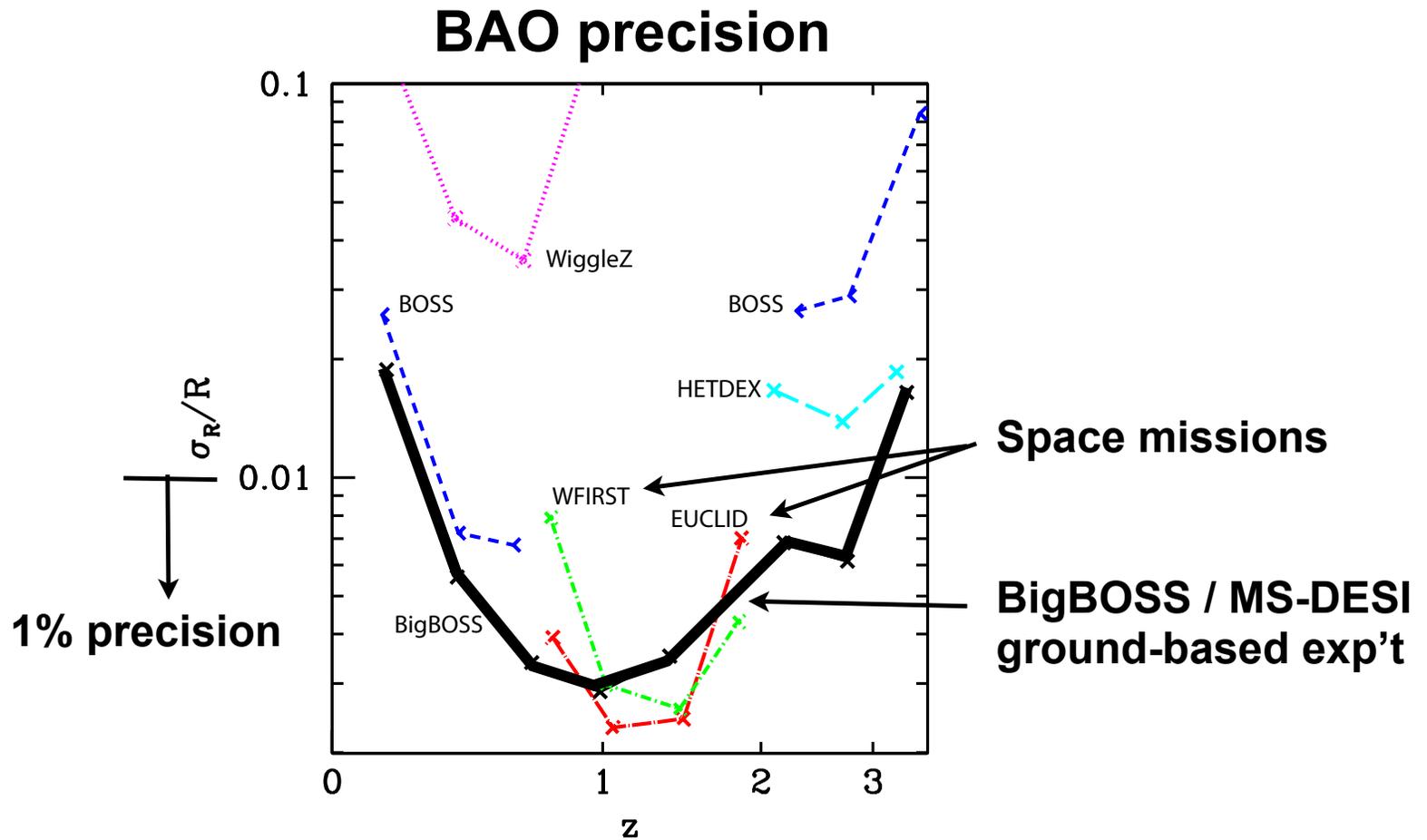
Λ +CDM



Λ +SIDM
 $\sigma/m = 1 \text{ cm}^2 / \text{g}$

Stage IV BAO science reach

Geometric probe with 0.3-1% precision from $z=0.5 \rightarrow 3$
35 measurements with 1% precision



Stage IV Imaging Surveys

	LSST	Euclid	WFIRST
Area [deg ²]	~12,000 (S Hemisphere)	~15,000	2,000 (in 440 days)
Source density n_{eff} [gal am ⁻²]	~30? [15 at Res>0.4]	33 [Res>0.4, S/N>18, $\sigma_e<0.2$]	75 [Res>0.4, S/N>18, $\sigma_e<0.2$]
Median z	0.8	0.8	1.3
Shape measurement filter	r + i	VIS (550—920 nm)	J + H + F184
Detectors	CCD	CCD (e2v)	HgCdTe (H4RG-10)
Photo-z filters	6 (ugrizy)	4 (VIS + YJH)	4 (YJH+F184)
Location	Ground	Space (L2)	Space (GEO)
FSF half light radius	~0.39" (median)	0.13"	0.12"
Exposures in filled shape survey	~700× 15 s (r+i)	3× 600 s	16× 184 s (6+5+5)

Number densities based on the COSMOS Mock Catalog – S. Lowel et al (2009)

Estimating Upcoming Cosmological Neutrino Mass Constraints

$$\frac{\Delta P(k)}{P(k)} \approx 1\% \approx -8 \frac{\Omega_\nu}{\Omega_m}$$

Hu, Eisenstein & Tegmark 1998

$$\Omega_\nu \approx \frac{\sum m_{\nu_i}}{93 h^2 \text{ eV}}$$

$$\implies m_\nu \lesssim (1\%/8) \times \Omega_m (93 h^2 \text{ eV})$$

$$\implies m_\nu \lesssim 20 \text{ meV}$$

Kaplinghat et al PRL 2003 (CMB WL)

Wang et al PRL 2005 (WL Clusters)

De Bernardis et al. 2009 (Opt. WL)

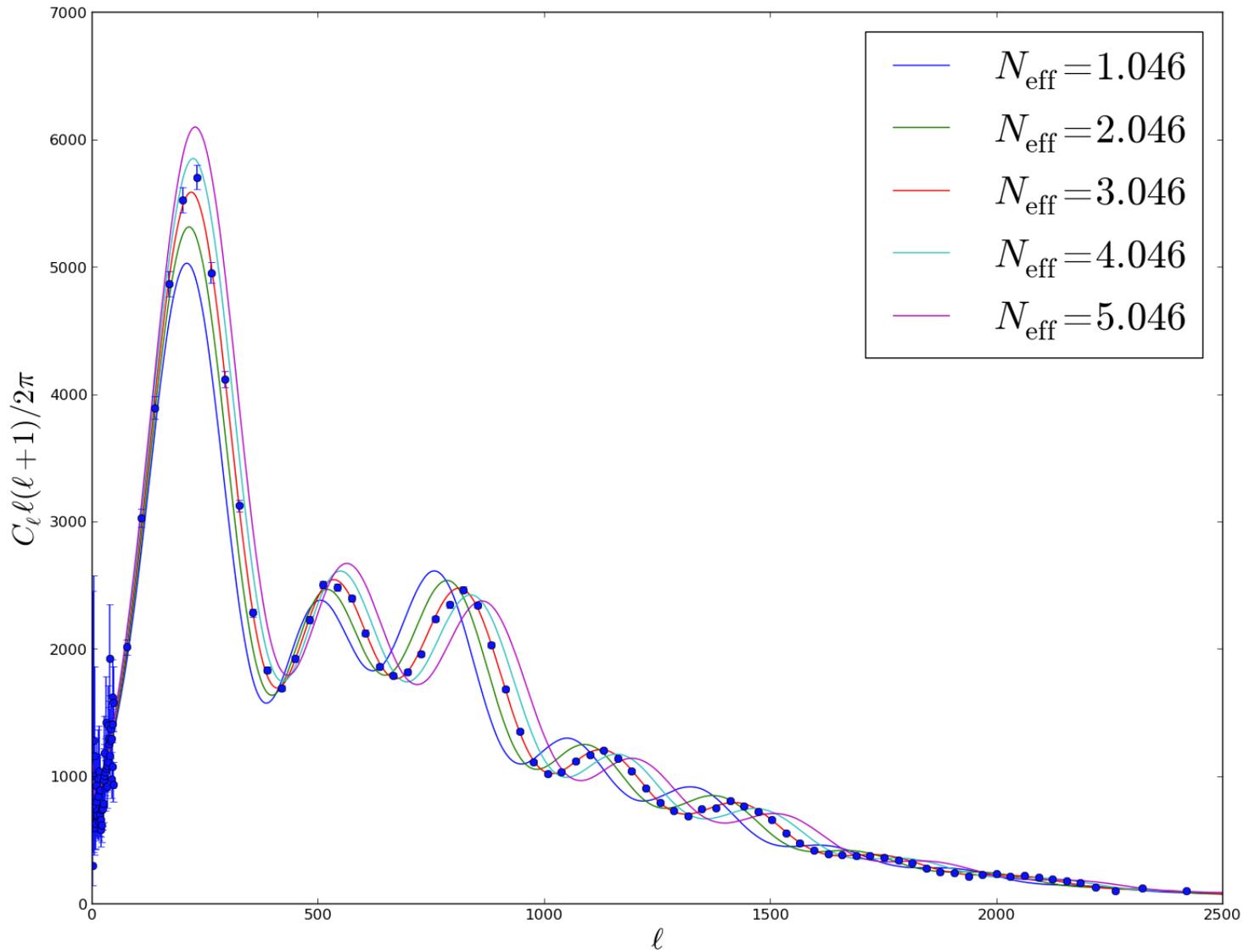
Joudaki & Kaplinghat 2011 (LSST)

Basse et al. 2013 (Euclid)

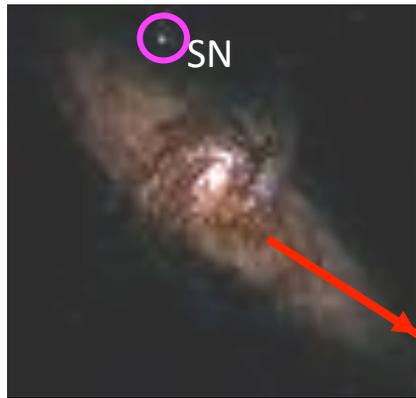
CF5 Neutrino Report 2013

K.N. Abazajian, Snowmass

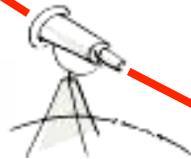
N_{eff} and Planck (A. Slozar, Snowmass)



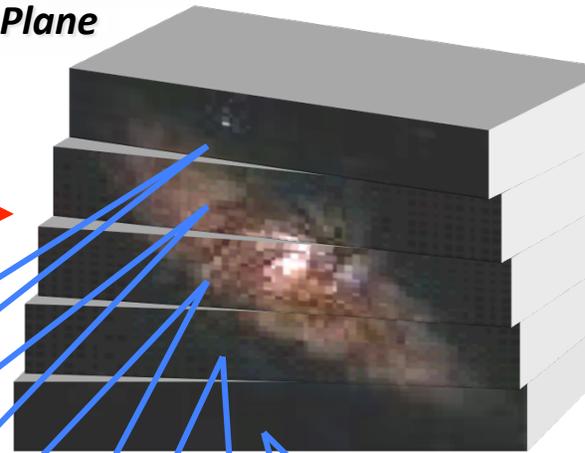
Integral Field Spectroscopy Concept



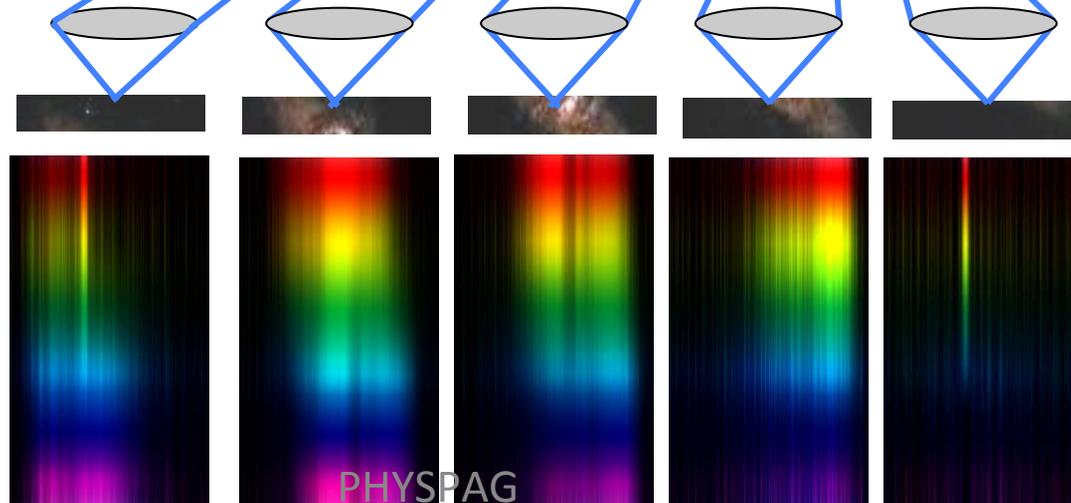
Telescope



Telescope Focal Plane



Slicer
Mirror
Array



Row of Pupil Mirrors

Row of Slit Mirrors

λ